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of the
St. Lawrence Estuary,
1974-1975

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Physical, chemical, and biological parameters of the
Saint John River Estuary, New Brunswick, Canada

by

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TABLE OF CONTENTS

	Page
Introduction	1
Physiography	1
Water Levels	3
Tides and Tidal Flow	3
Methods	4
Sediment Analysis	4
Water Analysis	4
Results and Discussion	5
Bottom Sediments	5
Temperature, Salinity, and Dissolved Oxygen	6
(1) Main Stem	6
(2) Kennebecasis Bay	7
(3) Belleisle Bay	8
(4) Washademoak Lake	9
Chlorophyll <i>a</i> and Physicochemical Parameters Related to Phytoplankton Production	10
Estuarine Circulation	10
(1) Main Stem	10
(2) Kennebecasis Bay	11
(3) Belleisle Bay and Washademoak Lake	12
References	12

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ABSTRACT

Metcalfe, C. D., M. J. Dadswell, G. F. Gillis, and M. L. H. Thomas. 1976. Physical, chemical, and biological parameters of the Saint John River Estuary, New Brunswick, Canada. Fish. Mar. Serv. Res. Dev. Tech. Rep. 686: 42 p.

The distribution of saline water and its circulation in the Saint John River Estuary are highly variable from year to year and are dependent on the seasonal discharge of fresh water from the Saint John River. Numerous sills at the mouth and within the estuary, which restrict tidal inflow, and a drainage basin area to estuary surface area ratio of 230:1 result in a freshwater-dominated system. The inland limit of the estuary fluctuates between the mouth and 60 km inland, and some inland freshwater basins are occasionally inundated with saline water.

Salinity distributions in various basins are characteristic of partially mixed, salt wedge, and stratified fjord estuaries. The restricted tidal flushing caused by the sills allow temperatures in the saline water of the estuary to rise to 18°C in summer as opposed to only 12°C in the Bay of Fundy. Poor mixing in some fjord-like basins caused oxygen levels to fall to 1.8 mg/l.

Various hydrographic features of the estuary are related to changes in water levels in the Saint John River, and fluctuating hydrographic conditions are analyzed for seasonal patterns. Total organic carbon and phosphate levels are higher and chlorophyll *a* levels lower than those reported for most temperate estuaries.

RÉSUMÉ

Metcalfe, C. D., M. J. Dadswell, G. F. Gillis, and M. L. H. Thomas. 1976. Physical, chemical, and biological parameters of the Saint John River Estuary, New Brunswick, Canada. Fish. Mar. Serv. Res. Dev. Tech. Rep. 686: 42 p.

La répartition et la circulation de l'eau salée dans l'estuaire de la rivière Saint-Jean varient grandement d'une année à l'autre et dépendent du débit saisonnier d'eau douce de la rivière. Les nombreux seuils qui s'opposent à la marée, à l'embouchure et dans l'estuaire, et le rapport de la superficie du bassin de drainage de la rivière à celle de son estuaire, qui est de 230:1 se traduisent par un système à dominance de l'eau douce. La limite à l'intérieur des terres de l'estuaire fluctue entre l'embouchure et 60 km de la côte; de plus, certains bassins intérieurs sont occasionnellement inondés par de l'eau salée.

La répartition de la salinité dans les divers bassins est caractéristique des estuaires-fjords où les eaux sont partiellement mélangées, et présentent un coin de salinité et une certaine stratification. Le mouvement restreint de la marée permet à la température de l'eau salée dans l'estuaire d'atteindre 18°C en été comparativement à 12° seulement dans la baie de Fundy. Le mauvais mélange des eaux dans certains bassins du genre fjord a fait chuter la concentration d'oxygène à 1,8 mg/l.

Les autres établissent une relation entre diverses caractéristiques hydrographiques de l'estuaire et les changements du niveau des eaux dans la rivière Saint-Jean, et analysent les fluctuations des conditions afin d'en déterminer les caractéristiques saisonnières. Les teneurs totales en carbone organique et en phosphates sont plus élevées et celles de la chlorophylle a, plus faibles que dans la plupart des estuaires tempérés déjà étudiés.

INTRODUCTION

The water circulation and distribution of salinity within estuaries have been classified into a number of categories by various authors (Hedgepeth 1951; Den Hartog 1960; Bowden 1967). Classification of estuarine systems, however, is often complicated by their dynamic nature. This is particularly evident in the Saint John Estuary where large fluctuations in freshwater discharge vary the circulation within a single basin from year to year or even season to season, and where the complex bottom topography produces several discrete basins with widely disparate types of circulation. In addition, some basins function as lakes for part of the year and estuaries for the remainder.

Although the Saint John is one of the better studied estuaries on the Canadian east coast, past investigations have been limited by short study periods and by the exclusion of inland portions of the estuary. Rogers (1936), in an unpublished thesis, presented temperature and salinity profiles for the estuary, including the only description to date of Belleisle Bay and Washademoak Lake. Hachey (1939) studied the hydrography of Saint John Harbour and the Reversing Falls gorge. Trites (1960) monitored physicochemical conditions in Kennebecasis Bay and Long Reach during 1957 and 1958, and Sprague (1964) repeated these investigations during December 1959. Neu (1960) studied currents and sediment transport in the lower estuary and harbour. MacDonald et al. (1970) monitored dissolved oxygen within the estuary as part of a pollution survey, and Gillis (1974) examined diurnal oxygen fluctuations, chlorophyll *a* concentrations, and nutrient loads throughout the system.

Differences among data from several of these studies indicate considerable annual variations in hydrographic conditions. Our data, which were derived from three concurrent biological studies carried out between 1972 and 1976, were sufficient for an understanding of these variations. Moreover, the data provide a comparison with conditions before the construction of the Mactaquac Dam on the Saint John River in 1967 and constitute a baseline for the assessment of the future effects of the Dickey-Lincoln Dam proposed for the upper river.

Physiography

The Saint John River Estuary empties into the Bay of Fundy from the southeastern corner of New Brunswick (Fig. 1). The exact boundaries of the estuary are difficult to define. The Venice system of estuarine classification (Den Hartog 1960) sets the chemical limits for estuaries at 0.3‰ and 16.5‰ chlorinity. This corresponds roughly to Hedgepeth's (1951)

salinity boundaries of 0.50/oo and 300/oo. Both definitions would place the seaward boundary of the estuary within the Bay of Fundy. As this was impractical for study, we followed several previous authors (Rogers 1936; Trites 1960; Sprague 1964) in setting Reversing Falls as the seaward limit (Fig. 1).

Pritchard (1967) argued that the inland limit of an estuary should be set at a salinity of 0.10/oo since the sea contributes 90% of the salt content at this salinity. Since the Saint John Estuary often contains large volumes of 0.1 to 0.50/oo brackish water, we have accepted his definition for the inland limit.

The upper estuary is situated within the New Brunswick lowlands, a broad alluvial plain underlain by Pennsylvanian sandstone (Potter et al. 1968). The valley here has gentle slopes and broad flood plains while the estuary is characterized by a shallow mean depth (7.2 m) and numerous islands, channels, and marshlands (Fig. 2). Below the confluence of Washademoak Lake the estuary enters the Caledonia Highlands, a region of syncline-anticline topography consisting of sedimentary and metamorphic rock (Potter et al. 1968). Here the valley narrows, the channel bed becomes irregular, and the mean depth increases to 12 m (Table 1, Fig. 2).

The most significant morphometric feature, in terms of its effect on the characteristics of the estuary, is the Reversing Falls sill. This shallow, 5-m-deep, rock sill is situated at the mouth of the narrow but deep gorge connecting the Grand Bay area of the estuary to the Bay of Fundy (Fig. 2). It restricts both estuary outflow and tidal inflow.

Kennebecasis Bay, Belleisle Bay, and Washademoak Lake are all "tributary" estuaries that enter the "main stem." Water circulation among all three bodies and the main stem is restricted by shallow sills at their mouths, particularly in Kennebecasis Bay, the morphometry of which resembles a true fjord (Fig. 2). Another sill at the mouth of Long Reach restricts circulation between the upper and lower main stem.

Table 1 summarizes some of the morphometric characteristics of different regions of the estuary. The total area and volume are 240 km² and 2.77 x 10⁹ m³, respectively. The three tributary estuaries account for 56% of the area and 70% of the volume. Kennebecasis Bay has the greatest maximum (62 m) and mean (21.9 m) depths.

The estuary has a total drainage area of 55,045 km², a ratio of drainage area to estuary surface area of =230:1. The Saint John River itself drains 93.2% of this total from regions extending into Maine, Quebec, and northwestern New Brunswick. Several small rivers drain a limited region around the estuary (Table 1).

Water Levels

Water-level and discharge data on the Saint John River and estuary are available for the past 40 years (Department of Environment, Canada). These data are the basis of the following description:

Water levels in the river peak in the spring and late autumn, but the extent, timing, and magnitude of the freshets vary from year to year (Fig. 3). Water levels are usually lowest in late summer and late winter owing to evaporation and freezing, respectively. During our study period, levels were far above the mean in the winter of 1973 and below it in the winter of 1975 (Table 2).

Water levels in the estuary are governed by the river to the extent that seasonal water level patterns and variability are identical (Fig. 4). Water levels and discharge of the river are closely related but there is often considerable day-to-day variation in discharge (Table 2).

Unlike the Bay of Fundy, which remains ice free in winter (Hachey 1939), the entire estuary, except for Reversing Falls gorge, is frozen over from late December until early April. During mild winters, however, large stretches of ephemeral ice or open water occur in regions with strong currents.

Tides and Tidal Flow

The Reversing Falls sill restricts the inflow and outflow of water, causing a reduction in the tidal range of the Saint John Estuary. Tidal range in Saint John Harbour is 8.1 m at springs and 6.9 m at neaps, but the range inside Reversing Falls sill never exceeds 0.7 m (Trites 1960). Figure 5 illustrates the water level fluctuation at Reversing Falls and in the estuary during one tidal cycle. At mean high tide in the harbour, the water level is 2 m higher than in the estuary (Neu 1960), and there is a strong inflow of saline water. As the level in the harbour falls below the level in the estuary the flow is reversed. A tide crest moves inland from the Reversing Falls and is retarded by shallow water in the upper estuary, so that at one point there are simultaneous tide crests in the lower and upper estuary (Fig. 5). The tide extends inland approximately 90 km to Fredericton and the head of Grand Lake (Fig. 1).

Neu (1960) calculated the theoretical volume of inflow and outflow through the Reversing Falls during a mean tidal cycle for various mean daily water levels at the estuary mouth (Fig. 6). During mean water levels the ratio between outflow and inflow volume is 1.67:1.00. High-water levels in the river reduce tide penetration and range in the estuary. Neu (1960) calculated that mean daily water levels at Reversing Falls exceeding 3 m, such as during the spring freshet, cause a continuous outflow through the gorge. There is a linear relationship between

water levels at the estuary mouth and in the Saint John River. This is represented by the equation

$$\underline{Y} = 1.12 + 1.91 \underline{X}$$

(where $\underline{Y}$ = Mactaquac water level; $\underline{X}$ = Indiantown water level). From this relationship it is possible to calculate that continuous outflows occur when river levels at Mactaquac exceed 6 m (Fig. 6).

METHODS

Sediment Analysis

Bottom sediments were collected at five substations along each of 29 transect stations within the estuary. Transect stations were located at 2-km intervals within the main stem and tributary basins. Samples were taken with either a 0.052-m²-tall Ekman grab in fine sediment, or a 0.023-m² Ponar grab in coarse sediment. Each sample was mixed and a subsample taken for particle-size analysis. The subsamples were frozen and later thawed and analyzed for percentage content of silt, clay, and sand by the hydrometer method of Bouyoucos (1962). Samples from inland areas of Kennebecasis Bay, however, were analyzed by the Andreason pipette method described by Holme and McIntyre (1971).

Samples were collected for total carbon analysis at the deepest station along selected transects. Three replicate samples were taken and all samples were frozen. Samples were later thawed, air-dried, and analyzed for total carbon content with a Leco induction furnace and carbon analyzer. Samples were dried at 105°C for 24 h; water content of the dried samples was calculated from loss of weight and accounted for in final calculations of carbon content.

Water Analysis

Samples were collected at the stations illustrated in Fig. 2. Stations K3, 6, 9, B2 and W1 were sampled at regular intervals throughout 1972 to 1976, usually bi-monthly; the other stations were sampled intermittently, usually during transition periods. Sampling was done from boats, river ferry, or through the ice.

Salinity was determined in the field with a Beckman RS5 salinometer or a Yellow Springs 33 salinometer, or water samples were collected for titration with silver nitrate in the laboratory. Since conductivity of local fresh waters are usually less than 70 µohm (Gillis 1974), all conductivity was assumed to be due to halides. Temperature was determined with a Beckman

RS5 salinometer, a Yellow Springs 33 salinometer, a Yellow Springs 54 oxygen meter, or a Yellow Springs 425C telethermometer. All were calibrated against a mercury thermometer. Dissolved oxygen concentrations were determined in fresh water ($<10/00$) with a Yellow Springs 54 oxygen meter or by Winkler titration, and saline water samples ($>10/00$) were analyzed in the field with a Delta 2010 oxygen analyzer.

Water samples for chlorophyll *a* analysis were taken from the surface and poured through 170- μ m nitex mesh into nalgene bottles. Several drops of magnesium carbonate suspension were added and the bottles were refrigerated overnight. Aliquots of each sample were filtered through 0.80- μ m membrane filters and the filters were placed in acetone for extraction. The extracts were analyzed for chlorophyll *a* with a Turner Model 111 fluorometer according to the method of Strickland and Parsons (1966).

Water samples were analyzed for total organic carbon, nitrates and nitrites, total phosphates, pH, water colour, and turbidity. Field measurements of pH for comparison were done with a Hach comparator. Water transparency was measured with a Secchi disk 20 cm in diameter.

RESULTS AND DISCUSSION

Bottom Sediments

The bottom sediments of the estuary are variable as a result of alternating scouring and deposition due to river and tidal currents and wave action. River currents in the shallow upper estuary have produced sandy sediments in deep water with deposition zones of silt and clay along the shoreline (Fig. 7). The central portion of Long Reach has a clay bottom, but the sediments of the eastern shore are a sand-clay mixture, which is probably a result of wave action. The mouth of Long Reach is scoured of lighter sediments by tidal currents (Fig. 7). Grand Bay contains a poorly sorted sediment of clay, silt, and sand (Fig. 7). Neu (1960) stated that these sediments originated from river-borne silt and clay particles that flocculated upon entering the saline lower estuary. He suggested that most flocculated material is deposited in Saint John Harbour and subsequently is resuspended with sand from the Bay of Fundy and carried back into the estuary by strong bottom currents. The region near the Reversing Falls gorge is scoured of lighter clay particles, probably owing to tidal currents.

Most of Kennebecasis Bay contains silts, with rubble and ledge rock in shallow water. Belleisle Bay sediments are a sand-silt-clay mixture, with sand predominating at the head and foot of the bay. Washademoak Lake sediments contain the most sand of the tributary estuaries.

Total carbon concentrations were highest in deep areas and maximum levels occurred in the deepest regions of Belleisle Bay (Table 3). Washademoak Lake, Long Reach, and Kennebecasis Bay all contained a high percentage of carbon. The scoured sediments of the upper main stem and Reversing Falls gorge contained the least.

Temperature, Salinity, and Dissolved Oxygen

(1) Main Stem

Temperatures at Station 6 fluctuated widely but followed a seasonal pattern (Fig. 8). Temperatures at the surface varied between 0 and 22°C and bottom temperatures fluctuated between 2 and 18°C. The saline water in Long Reach is formed by the mixing of surface water from the Bay of Fundy and estuary water in the Reversing Falls gorge (Hachey 1939). Although tidal mixing at Reversing Falls is great, there is a relatively low rate of saltwater exchange between the Bay of Fundy and the estuary (Neu 1960). As a result, temperatures on the bottom at Station 6 are intermediate between those of the two sources (Fig. 9), and surface temperatures are much higher in the estuary than in the bay. Bottom temperatures at upstream stations show the decreased moderating influence of the Bay of Fundy and the increased influence of the seasonal river temperatures (Fig. 10).

Salinities at Station 6 varied between 0 and 21‰ (Fig. 11). Fluctuations in halocline depth and salinity were related to water level changes (Fig. 12). During the spring freshet, salinities throughout the water column decreased to near 0‰, and during summer the salinities gradually rose to greater than 20‰. Salinities decreased during the winter of 1976 but there was no marked decline during the winters of 1974 and 1975 (Fig. 11).

During May 1973, and again in April and May 1976, saline water was entirely absent from the main stem of the estuary but, in September 1975, saline water extended 60 km above the harbour to Gagetown (Fig. 13). These observations represent the maximum and minimum penetration of saline water during the study period, and they indicate the variability of saline penetration into the estuary.

The position of the saline front is dependent upon the flow of fresh water from the Saint John River (Fig. 14). Increased water levels reduce saline penetration, and water levels corresponding to continuous outflows at the Reversing Falls (Fig. 6) flush all saline water from the main stem. Because of the dominance of the river, the saline penetration is unstable and flushing commonly occurs on an irregular basis at times other than spring, as happened in December 1959 (Sprague 1964).

The Mactaquac Dam appears to have raised the minimum yearly water level in the river, but examination of data taken before its construction (Rogers 1936; Trites 1960) indicates that saline penetration has not been significantly altered.

Fig. 13a illustrates the theoretical oscillations of the inland limit of the estuary in relation to mean monthly water levels in May, July, September, December, and February. The saline limit retreats during spring and autumn freshets, and advances during summer and winter. Actual observations of monthly water levels (Table 2) and saline penetration (Fig. 13b) often differ significantly from the mean pattern. In the winters of 1973 and 1976, the saline front was located close to its theoretical mean position, as it was in 1959 (Trites 1960) and 1960 (Sprague 1964). During the winters of 1974 and 1975, however, as well as during 1935 (Rogers 1936), the front was further inland owing to low water levels. Figure 12b illustrates the salinity zones within the estuary according to the classification of Hedgepeth (1951), with the addition of an extra zone of 0.1-0.5‰ salinity. The persistence of brackish water of this salinity over large areas of the estuary is unusual and perhaps of some biological consequence. The majority of the estuary, however, is meso- or poly-haline throughout much of the year.

MacDonald et al. (1970) found that all areas within the main stem of the estuary contained relatively high concentrations of dissolved oxygen. Data from Station 6 in Long Reach support these findings, although there was slight oxygen depletion at intermediate depths during a low-water period in August 1972 (Fig. 15d and e). Presumably, discharge and tidal circulation keep oxygen concentrations high at the surface and bottom, respectively. Higher water levels in March 1976 produced uniformly high oxygen concentrations throughout the water column (Fig. 15e).

(2) Kennebecasis Bay

The deep basin of Kennebecasis Bay maintains the most stable physical and chemical environment in the estuary. Temperatures in deep water generally remained constant over long periods but sharp changes were observed during late summer and winter. At Station K3 yearly variation was between 4 and 14°C (Fig. 8). Surface temperatures followed the normal seasonal trend.

Deep-water salinities were relatively constant throughout the study period and at Station K3 varied between 19 and 22‰ (Fig. 11). Surface salinities fluctuated between 1 and 11‰, depending on river flow. There was always a well defined halocline between 4 and 10 m (Fig. 11). The surface salinity and halocline depth were apparently governed by water levels in the Saint John River, but local freshets in the Kennebecasis River probably affected surface conditions as well.

The deep water was usually depleted of oxygen during the spring and early summer (Fig. 15a) but autumn and winter oxygen levels were generally high (Fig. 15b).

An intensive survey of Kennebecasis Bay was conducted throughout 1974-75 to determine the mechanism responsible for the observed temperature and dissolved-oxygen changes in the deep-water zone. Physical and chemical conditions in early August 1974 (Fig. 16) indicated that the large volume of water below the halocline was essentially trapped within the bay by the sill at its mouth. This agrees with Trites' (1960) assessment of conditions during the summer of 1957 and conforms to the theoretical model of a stratified fjord estuary (Rattray 1967). By late August, however, the longitudinal distribution of density, temperature, and dissolved oxygen isopleths indicates that salinities in the lower main stem (Station 2) had risen to a point where dense, saline water passed over the sill, flowed in along the bottom of the bay, and began displacing the water within the deep layer (Fig. 12). This resulted in the rapid large temperature and dissolved-oxygen changes noted at Station K3. Trites (1960) observed a similar inflow in September 1957 but he found no evidence of further inflows during the following autumn and winter. Density, temperature, and oxygen fluctuations observed in January (Fig. 18) and March (Fig. 19) 1975 indicate that inflows take place during the winter as well.

The sharp temperature changes that occurred during the late summer of 1973, 1974, and 1975 (Fig. 8) indicate that inflows occurred regularly during those summer months when monthly mean water levels in the main stem were less than 3.5 m (Fig. 12). During winter, inflows were found to occur when monthly mean water levels fell below 3.7 m (Fig. 12b). High-water levels delayed inflows until late March in 1976, resulting in above-normal temperatures (Fig. 8) and low oxygen levels (Fig. 15c) in the deep water for much of the winter. A similar delay may explain the absence of inflows during the winter of 1958 (Trites 1960).

Threshold water levels are lower during the summer months because temperatures at sill depth are lower within the bay than at Station 1, while the reverse is true during the winter. During an "average" year the monthly water levels fall below the threshold in July, August, September, and January (Table 2).

(3) Belleisle Bay

Physicochemical conditions within Belleisle Bay were the most variable in the estuary. This bay alternately resembles a fjord estuary or a freshwater lake for extended periods of time, depending on river flows during critical periods of the year.

During 1973 and 1974 the bay resembled a type II, dimictic lake (Hutchinson 1957) with 12°C hypolimnion, a thermocline between 10 and 20 m in the summer and a reverse thermocline

in winter. Winter bottom temperatures were low ($<2^{\circ}\text{C}$) as a result of circulation between the bay and the river. The influx and retention of saline water during the late summer and winter of 1975-76 created a reverse thermocline and resulted in high bottom temperatures (Fig. 8).

Salinities in the bay varied between 0 and $7.5^{\circ}/\text{oo}$ over the study period (Fig. 11). Between 1973 and 1975 the bay contained fresh water following the spring freshet, and during these "average" years it was inundated with variable amounts of saline water in the late summer and/or the late winter (Fig. 13a and b). Inflows of saline water occurred when month mean water levels fell below 3.5 m in summer and below 3.7 m in winter (Fig. 12). Cold water in the "hypolimnion" of the bay retards the inflow of warm saline water during the early summer months. The spring of 1976 was unusual in that the freshet did not purge the bay of saline water from the previous autumn. This was probably a result of the higher-than-normal salt concentration of this inflow (Fig. 11).

In September 1974, the deep water of Belleisle Bay contained less oxygen than the surface water (Fig. 15f) and this suggests that there is oxygen depletion during the summer with little mixing between the epi- and hypo-limnion. Inflows in autumn and winter oxygenate the deep-water zone (Fig. 15g) but absence of winter inflows in 1976 resulted in depletion of oxygen to 4.2 mg/l (Fig. 15h).

(4) Washademoak Lake

This tributary of the estuary normally functions as a type II, dimictic lake (Hutchinson 1957). Bottom temperatures varied between 0 and 19°C over the study period (Fig. 8d). Because of basin morphometry, the thermocline gradient was never steep and was established for only about 3 mo each summer (Fig. 8). Water temperatures were therefore relatively homogeneous from surface to bottom for much of the year.

Salinities varied between 0 and $1.5^{\circ}/\text{oo}$ (Fig. 11d). Saline water appeared intermittently and was usually distributed homogeneously throughout the water column. This saline water was readily flushed from the basin by increased freshwater flows.

Washademoak Lake does not receive a saline inflow during an average year but, in three instances during the study period, water levels were sufficiently low to allow saline water to enter (Fig. 13a and b). Inflows occurred during months when mean water levels fell below 3.0 m in summer and 3.5 m in winter (Fig. 12d). Table 2 indicates that these levels do not occur during an average year. Rogers (1936) also reported low salinities in Washademoak Lake in the summer of 1935.

Chlorophyll α and Physicochemical Parameters Related to Phytoplankton Production

Table 4 summarizes the chlorophyll α concentrations and physical and chemical factors related to primary production in the surface waters of the estuary during May to September throughout the study period. Secchi readings were relatively low throughout the estuary as a result of high water colour and turbidity. Transparency was lowest during the spring freshet but it increased throughout the summer months. The pH was slightly lower in areas dominated by fresh water and at all stations there was an increase in pH during the summer, possibly as a result of primary production.

Total organic carbon levels were high throughout the estuary but there was no seasonal or spatial trend to the readings. Total phosphates were relatively high at all stations in comparison with levels in other temperate estuaries (Ketchum 1969), and levels remained constant throughout the summer. Nitrate and nitrite concentrations gradually decreased during May to August in Kennebecasis Bay and Belleisle Bay, but levels increased again after late August (Fig. 20). Winter et al. (1975) noticed a similar depletion of nitrates in a fjord estuary as a result of phytoplankton utilization and vertical mixing insufficient for nutrient replenishment. It is possible that entrainment during the inflows of late summer replenished inorganic nitrogen lost from the surface waters of Kennebecasis and Belleisle Bays.

Chlorophyll α levels were relatively low as compared to those of other temperate estuaries (Ketchum 1969) and this condition may have been caused by low light penetration or limiting concentrations of nitrate. Highest levels occurred after ice break-up. Tributary estuaries contained more chlorophyll α than the main stem.

Estuarine Circulation

(1) Main Stem

During low-water periods the longitudinal, salinity, isopleth configuration in the main stem resembles that of a moderately stratified estuary (Fig. 21a). Salt content of both upper and lower water layers increases towards the sea, and there is no sharp halocline. This situation is similar to that found in the Miramichi estuary (Bousfield 1955) and the Penobscot estuary (Haefner 1967). In estuaries of this type the dominant mixing agent is turbulence caused by tidal action and, in this case, the turbulence is mainly confined to the Reversing Falls area (Neu 1960). Data for Fig. 20a were taken during low tide and the salinity isopleths clearly indicate that the sill at the mouth of Long Reach restricts tidal circulation within the upper main stem.

During intermediate water levels the estuary resembles a "salt wedge" (Fig. 21b). In this case the dominant action of the river forms a predominantly fresh surface layer and a sharp, wedge-shaped saline interface. Increased river flow causes the interface to tilt and migrate towards the sea until saline water is purged from the estuary (Fig. 21c). The two types of circulation in the main stem are a result of the large variation in river flow over the year.

Flushing rates of river water from the estuary were calculated by the method of Ketchum (1950) (Table 5); salinity distributions and discharge data illustrated in Fig. 21 were used. During the low-flow periods in September 1975, fresh water was flushed from the estuary 39.4 days after it entered saline water at Station 10. During medium flows in July 1974, the fresh water left the estuary 10.4 days after it entered saline water at Station 7, and in only 0.1 days at high flow. These flushing rates are comparable to those calculated by Ketchum (1950, 1951) for the New York Bight and the Rariton River and Bay, New Jersey, which were 0.6 to 11 days and 15 to 30 days for high and low flows, respectively.

(2) Kennebecasis Bay

Kennebecasis Bay undergoes two types of circulation, depending on high-water levels in the main stem. During periods of high-water levels primary circulation takes place in the upper layers only, which is typical of some fjords (Rattray 1967). Low-water levels, however, allow the intermittent inflow of saline water into the deep-water zone of the bay (Fig. 17 and 18). This deep circulation is characteristic of other fjords with deep sills at their mouths (Lafond and Pickard 1975; Anderson and Devol 1973). The Saguenay Estuary (Drainville 1968) is particularly analogous to this system, but the Kennebecasis fjord is unique in that surface flow in the main stem, a lateral system, is the primary factor controlling deep-water renewal.

The volumes of saline water that entered the bay during inflows in 1974-75 were calculated from changes in the concentration of dissolved oxygen by the method of Lafond and Pickard (1975) (Table 6). Between August and October 1974, there was a replacement of approximately 25% of the volume of the bay (Fig. 17). The inflow of January 1975 replaced 10% of the volume (Fig. 18) and an inflow in March 1975, only 9% (Fig. 19). The last inflow, although the smallest, penetrated the farthest into the Bay. Therefore, the velocity and not the duration of the inflow may be the dominant factor governing inflow penetration. A short-time series of data between 6 and 21 August 1975 indicates that a volume of approximately $6 \times 10^5 \text{ m}^3$ passed inward over the Kennebecasis sill during each tidal cycle.

(3) Belleisle Bay and Washademoak Lake

Belleisle Bay and Washademoak Lake received intermittent inflows of saline water that was usually distributed homogeneously throughout the water column, probably because of wind-driven circulation. An unusually large inflow into Belleisle Bay in the autumn of 1975 replaced 29% of the volume of the bay, according to calculations by the method of Lafond and Pickard (1975), and produced a highly stratified saline layer along the bottom (Fig. 22). The persistence of this layer during the following winter and spring freshets, and its depleted oxygen levels, indicated that there was little circulation across the halocline. The variable salinity conditions in these two tributaries defy any attempt at estuary classification.

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Table 1. Morphometry and hydrography of the Saint John River Estuary.

	Surface area (ha)	Volume (m ³ x10 ⁷)	Max. depth (m)	Mean depth (m)	Drainage area (km ²)
<u>Main Stem</u>					
Gagetown-Evandale	1979	10.2	19.9	7.2	
Evandale-Oak Point	409	5.0	25.2	12.4	
Long Reach	4869	38.7	42.1	10.2	51445
Grand Bay	3310	24.2	30.2	7.8	
Reversing Falls Gorge	<u>230</u>	<u>4.4</u>	<u>49.8</u>	<u>19.3</u>	
Sum	10797	82.5			51445
% Total	0.44	0.30			93.2
<u>Tributary Estuaries</u>					
Washademoak Lake	3816	23.0	30.2	6.1	1500
Belleisle Bay	2807	28.5	30.8	12.5	500
Kennebecasis Bay	<u>6968</u>	<u>143.2</u>	<u>62.0</u>	<u>21.9</u>	<u>1600</u>
Sum	13591	194.7			3600
% Total	0.56	0.70			6.8
Cumulative Total	24388	277.1x10 ⁹ m ³			55045
	≈240 km ²				

Table 2. Mean monthly water levels and discharge in the Saint John River at Mactaquac for 1966-75.

Monthly water levels during study period					Mean water level	Mean discharge (m ³ /sec)
	(m)			(1966-1975)		
	1972	1973	1974	1975	(m)	
Jan.	3.40	3.91	3.96	3.45	3.70 ± 0.49	346
Feb.	3.08	4.34	3.35	3.27	3.75 ± 0.48	297
Mar.	3.98	4.53	3.91	3.49	3.95 ± 0.58	481
Apr.	4.37	6.27	4.91	4.50	5.15 ± 0.73	1869
May	6.99	6.38	7.09	6.36	6.14 ± 0.83	3169
June	4.61	4.22	4.39	4.29	4.15 ± 0.38	784
July	3.85	3.79	3.60	3.15	3.46 ± 0.24	387
Aug.	3.75	3.51	3.27	3.20	3.38 ± 0.23	325
Sept	3.77	3.36	3.22	3.13	3.44 ± 0.38	457
Oct.	3.95	3.34	3.36	3.23	3.67 ± 0.49	548
Nov.	4.17	3.18	3.34	3.71	3.74 ± 0.53	579
Dec.	3.82	4.74	3.72	3.63	3.87 ± 0.44	624

Table 3. Total carbon content as % dry sediment weight and standard deviation in sediments of the Saint John River Estuary.

Station	Mean % carbon content
1	0.85 ± 0.05
2	1.71 ± 0.18
3	2.30 ± 0.10
6	4.70 ± 0.43
7	3.65 ± 0.27
9	1.95 ± 0.27
K1	1.81 ± 0.18
K2	2.71 ± 0.13
K3	2.93 ± 0.07
B1	2.57 ± 0.02
B3	4.95 ± 0.13
W1	3.22 ± 0.06
W2	3.78 ± 0.05

Table 4. Summer (May-Sept.) chlorophyll *a*, secchi depth, turbidity, colour, total organic carbon (T.O.C.), nitrate and nitrite, total phosphate, and pH in surface waters of Saint John River Estuary.

Station		Chl. <i>a</i> (µg/l)	Secchi depth (m)	Turbidity	Colour	T.O.C. (mg/l)	Nitrate and nitrite (mg/l)	Total phosphate (mg/l)	pH
F5	Max	8.92		3.3	30.0	11.0	0.170	0.040	7.3
	Mean	1.72		1.3	18.3	6.5	0.050	0.020	7.0
	Min	1.02		0.2	10.0	3.0	0.005	0.005	6.7
F3	Max	3.71	3.0	2.8	30.0	9.0	0.180	0.025	7.5
	Mean	1.46	2.2	1.2	25.0	5.0	0.090	0.019	7.2
	Min	0.87	1.9	0.2	20.0	2.4	0.050	0.008	6.9
3	Max	2.78		0.6	40.0	13.0	0.320	0.055	7.2
	Mean	0.78		0.4	35.0	7.8	0.170	0.020	7.0
	Min	0.43		0.2	30.0	4.0	0.020	0.005	6.7
6	Max	1.21	3.0	3.2	50.0	11.5	0.280	0.030	7.3
	Mean	0.49	2.0	1.0	40.0	7.8	0.160	0.017	7.0
	Min	0.41	1.5	0.3	20.0	6.0	0.005	0.010	6.8
B2	Max	3.36	3.5	1.0	30.0	9.0	0.220	0.013	7.4
	Mean	2.42	2.7	0.5	28.0	6.8	0.150	0.010	7.0
	Min	1.01	1.7	0.2	20.0	5.0	0.045	0.005	6.3
W1	Max	1.91	3.0	1.4	70.0	12.5	0.320	0.030	7.4
	Mean	1.60	2.5	1.0	55.0	8.0	0.150	0.020	7.0
	Min	1.01	2.0	0.5	50.0	3.0	0.010	0.010	6.2

Table 5. Flushing rate in the Saint John Estuary during high, medium, and low river discharge.

Mean daily river discharge (R) (x 10 ⁷ m ³)	Accumulated freshwater volume (F) (x10 ⁷ m ³)				Total (F _t)	Flushing rate (T = F _t /R)
	Reversing Falls Gorge	Grand Bay	Long Reach	Upper Estuary		
Low flow - 1.24	1.6	12.7	21.4	13.1	48.9	39.4
Medium flow - 4.20	0.7	17.9	24.8	-	43.5	10.4
High flow - 40.42	4.3	-	-	-	4.3	0.1

$$F = \frac{S_o - S}{S_o}$$

Where: S_o = Salinity of water outside the estuary
which mixes with fresh water = 290/00,
S = Salinity at any point within the estuary.

Table 6. Volume of Inflow into Kennebecasis Bay during 1974-75.

Date	Pi	Pb (mg/l)	Pa	Vt ($\times 10^7$ m ³)	Vi ($\times 10^7$ m ³)	% of vol. in Kennebecasis Bay
Aug. 6-21	7.3	2.2	5.5	2.43	1.62	6.1%
Aug. 21-Sept. 16	7.3	5.9	6.7	8.69	4.96	18.9%
Sept. 16-Oct. 30	8.0	6.7	6.8	0.64	0.05	0.2%
Dec. 10-Jan. 23	8.5	6.5	7.4	3.23	2.65	10.1%
Jan. 23-Feb. 26	9.5	7.4	7.6	0.64	0.07	0.3%
Feb. 26-Mar. 12	10.5	7.7	8.3	10.69	2.29	8.7%

$$Vi = Vt \cdot (Pa - Pb) / (Pi - Pb)$$

Where: Vi = Volume of water entering estuary during inflow,
Vt = Volume of water in estuary affected by inflow,
Pb = O₂ content of estuary water before inflow,
Pa = O₂ content of estuary water after inflow,
Pi = O₂ content of water entering estuary.

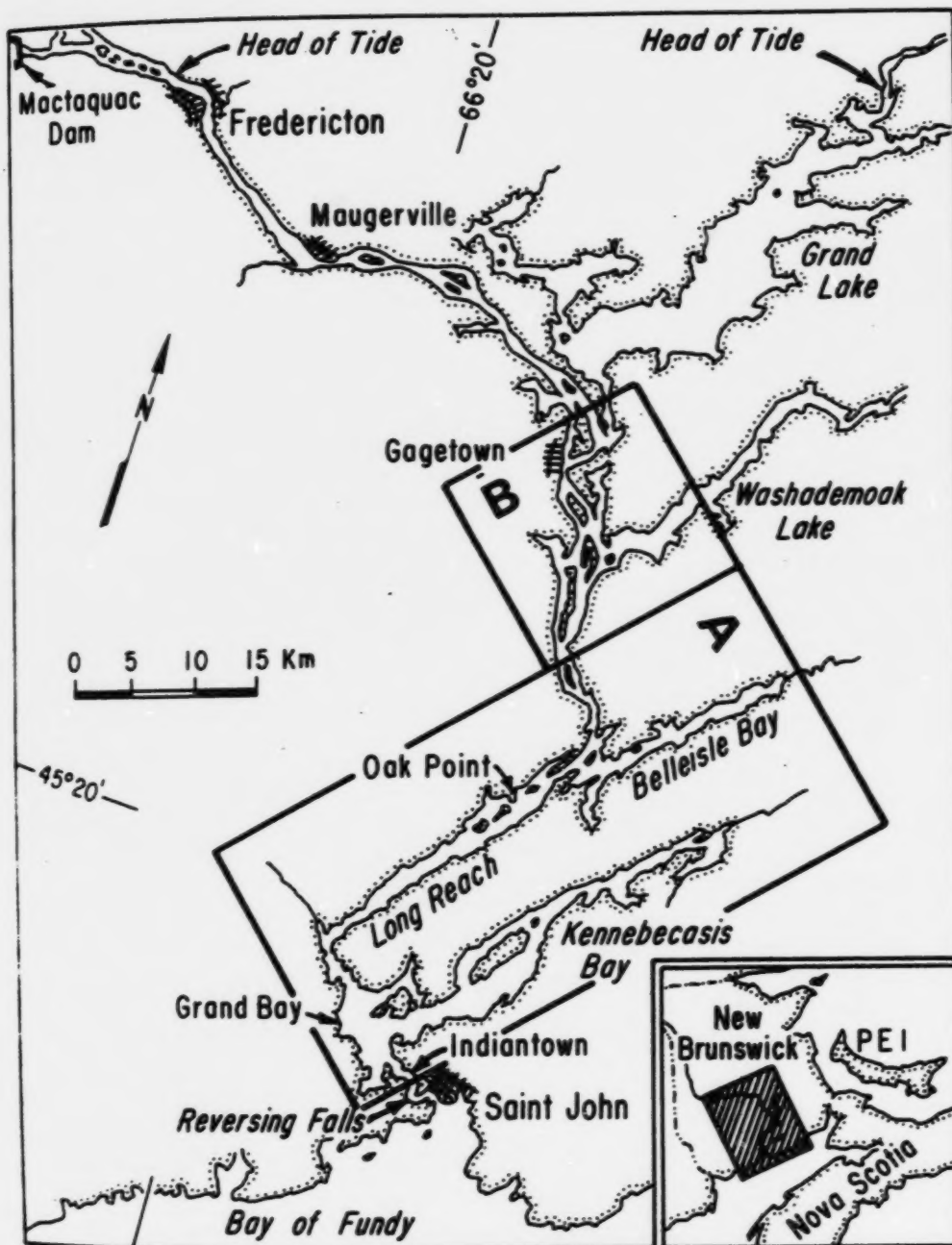


Fig. 1. The Saint John River Estuary, indicating place names referred to in the text.

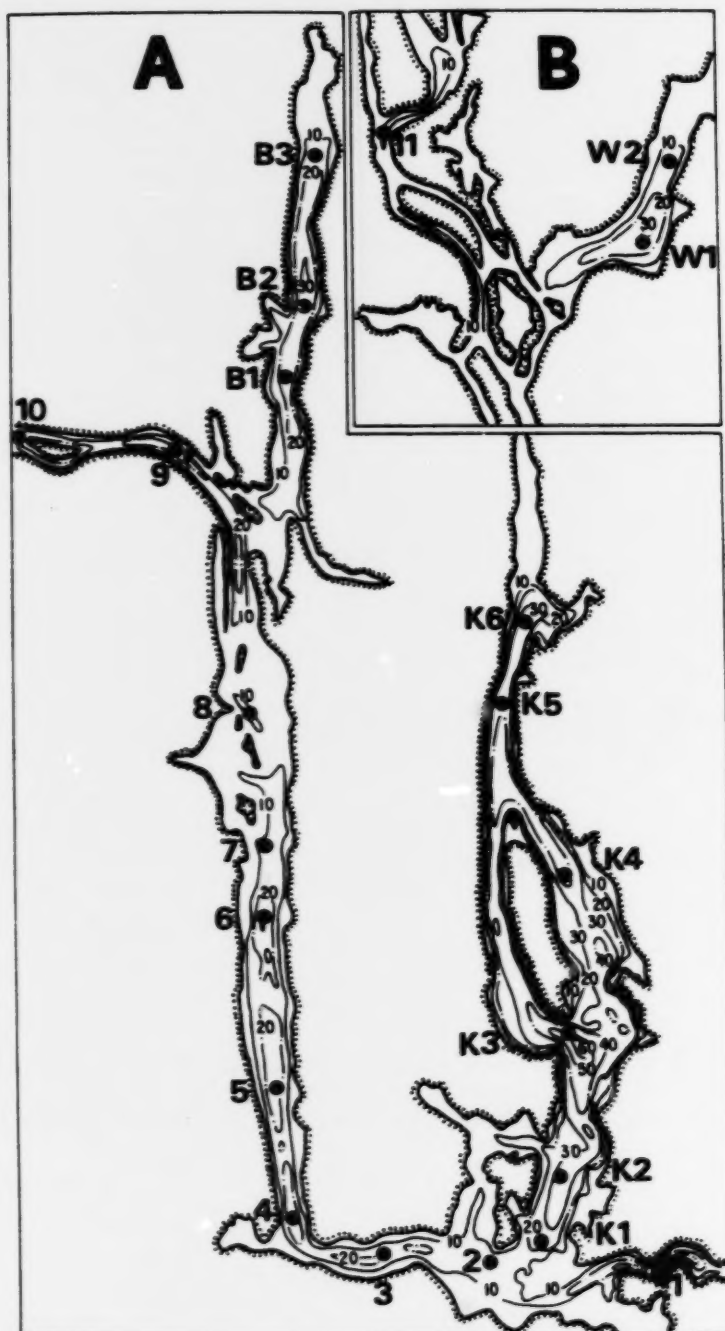


Fig. 2. Sampling stations taken in, and morphometry of, the Saint John Estuary.

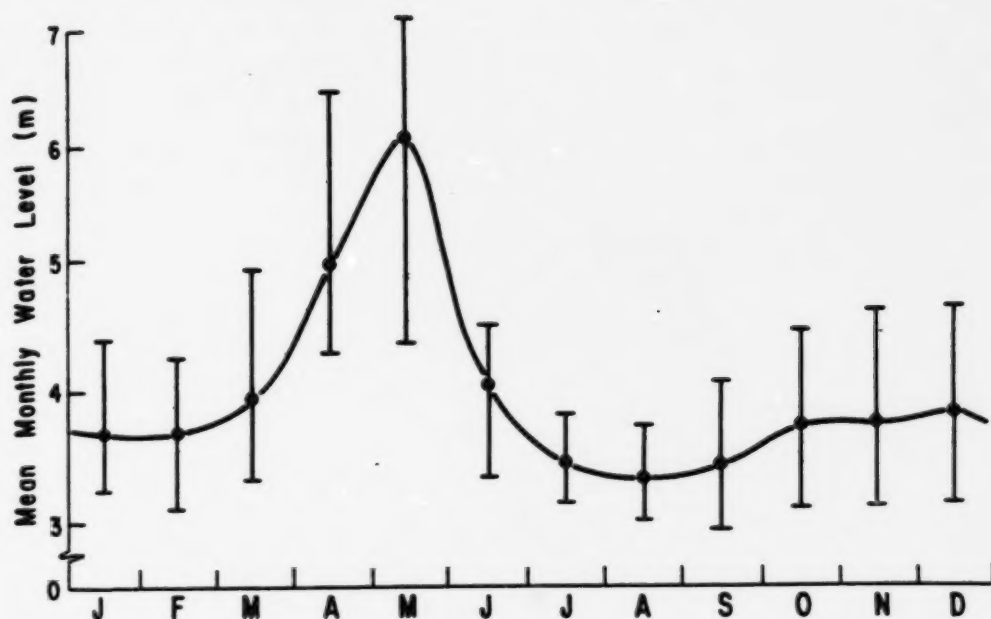


FIG. 3. Maximum, minimum, and average mean monthly water levels in the Saint John River at Mactaquac Dam for 1966-75 (from Water Quality Branch, Environment Canada).

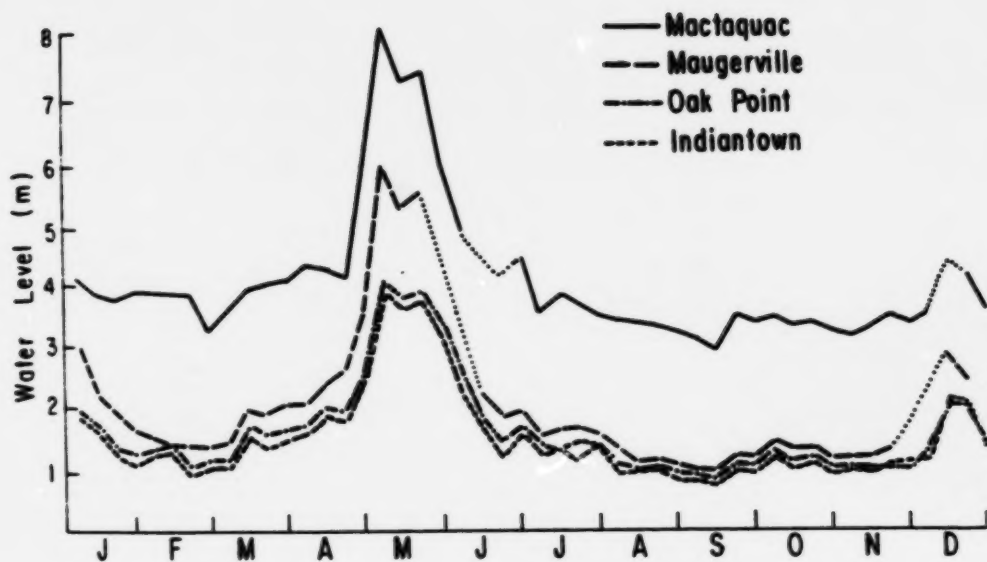


Fig. 4. Mean weekly water levels at four points in the Saint John River and Estuary during 1974 (from Water Quality Branch, Environment Canada).

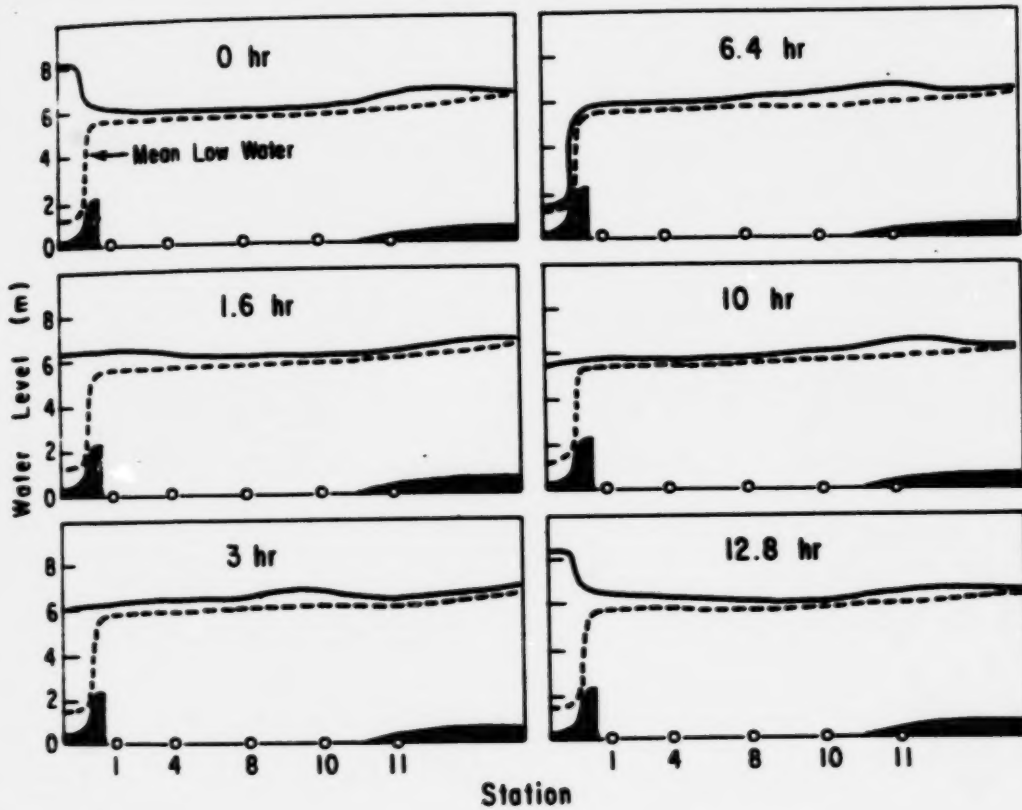


FIG. 5. Tidal fluctuation and movement of the tidal crest in relation to time in the Saint John Estuary. The sill at Station 1 is Reversing Falls.

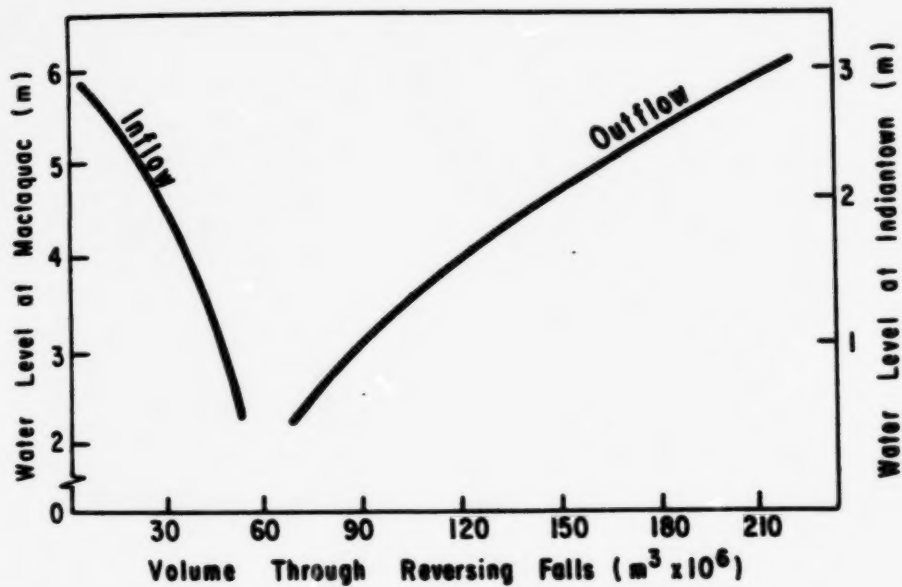


Fig. 6. Volume of inflow and outflow through the Reversing Falls at different water levels during a mean tidal cycle (after Neu 1960).

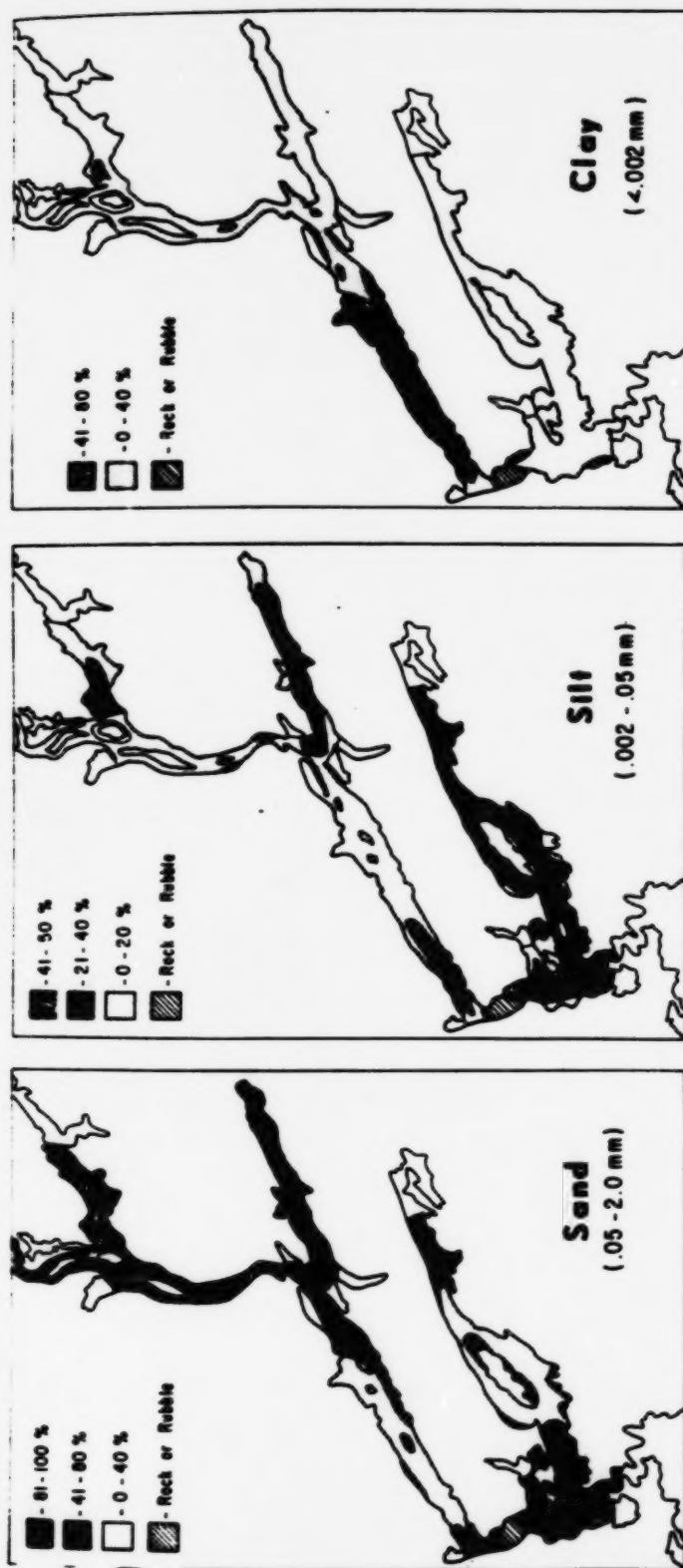


Fig. 7. Composition of bottom sediments in the Saint John Estuary.

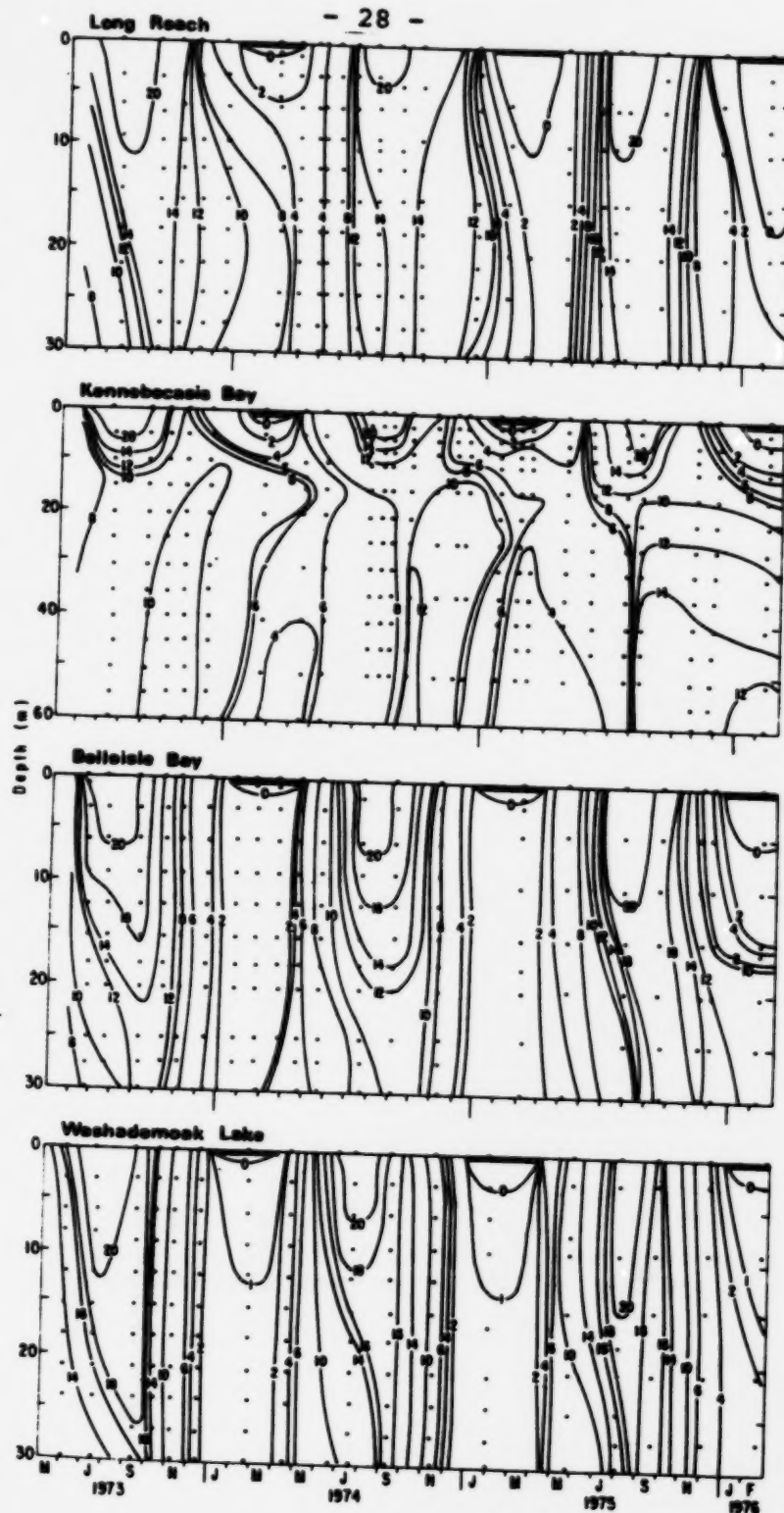


Fig. 8. Temperature isopleths at selected stations during 1973 to 1976. Station 6, Long Reach; Station K3, Kennebecasis Bay; Station B2, Belleisle Bay; Station W1, Washademoak Lake.

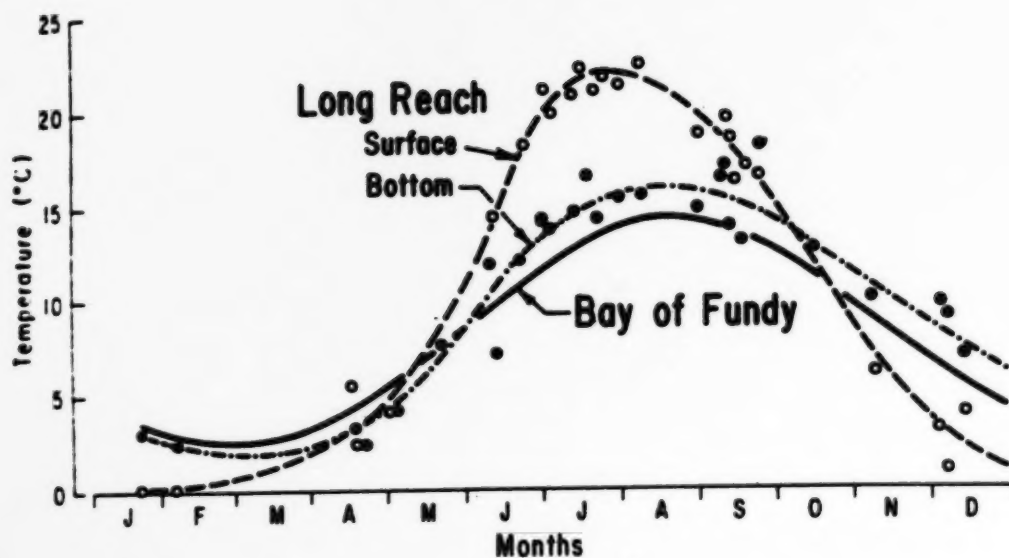


Fig. 9. Mean yearly temperature fluctuation at the bottom and surface in Long Reach (Station 6) and in the Bay of Fundy.

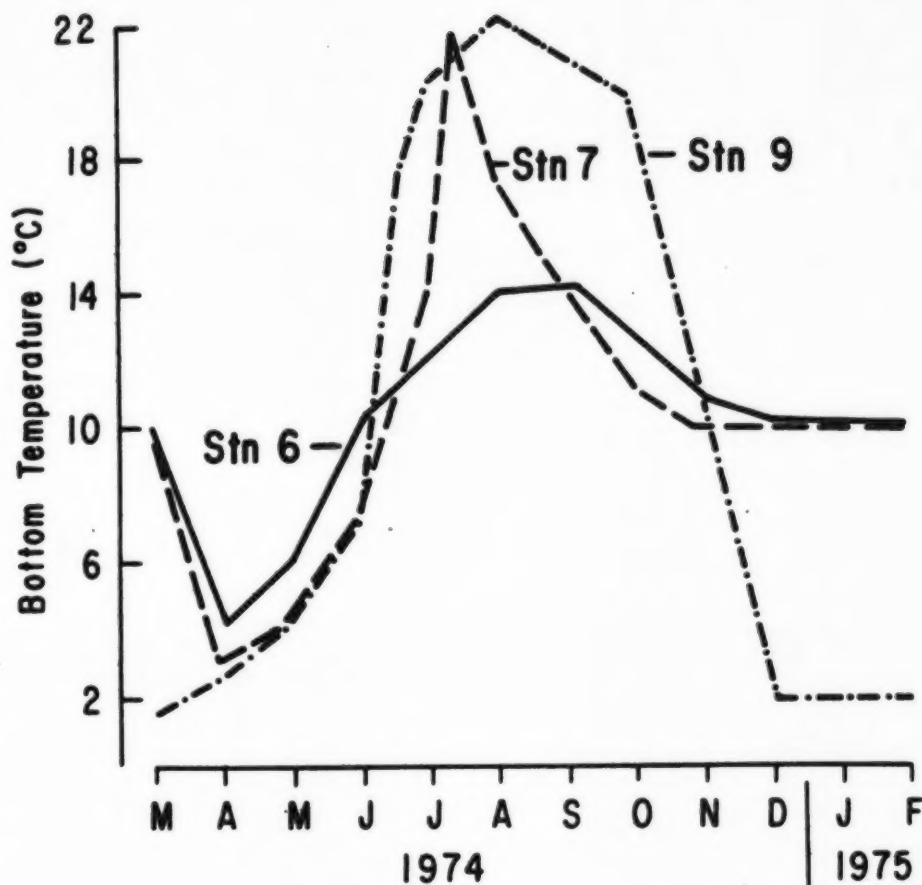
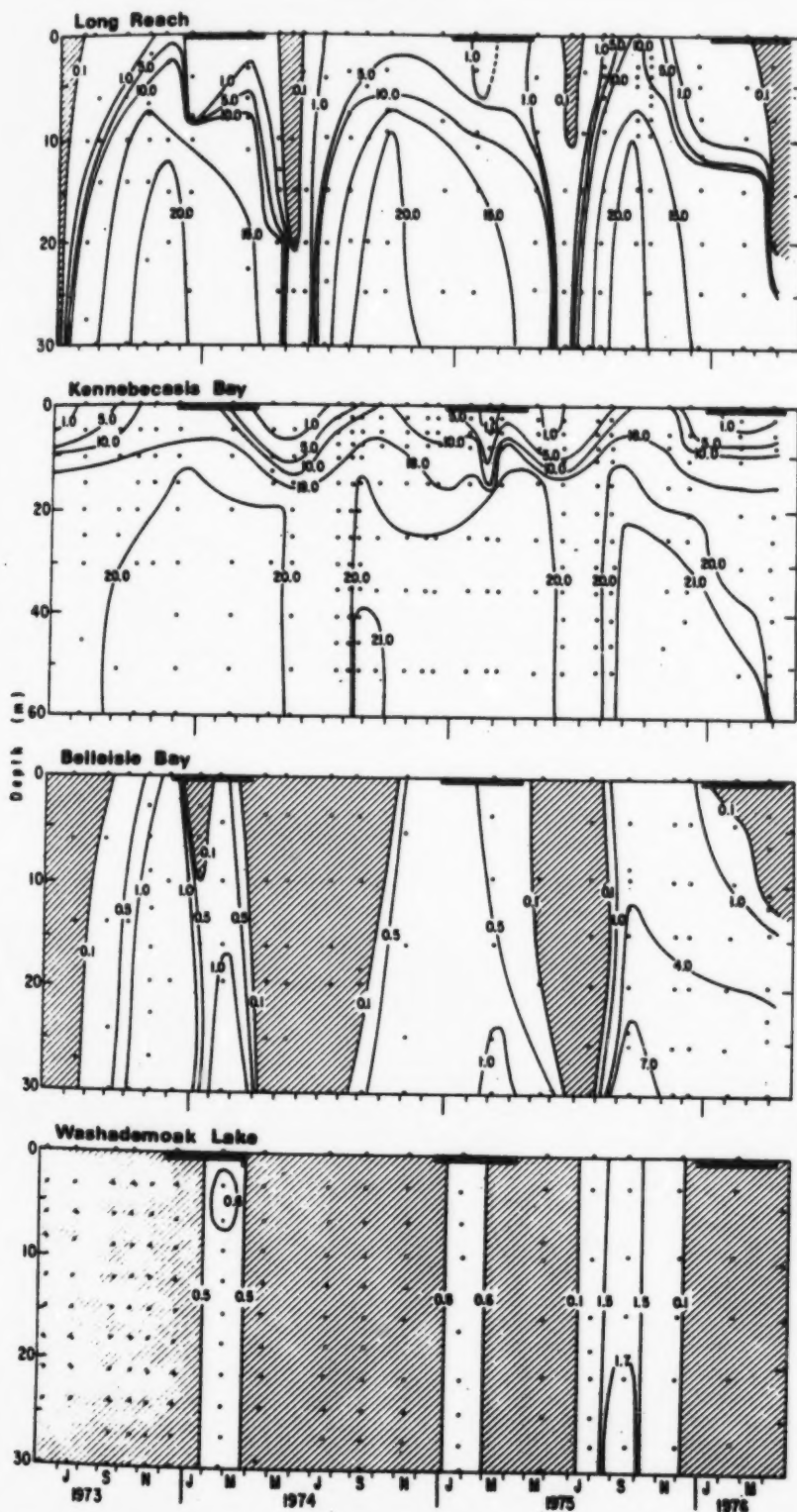
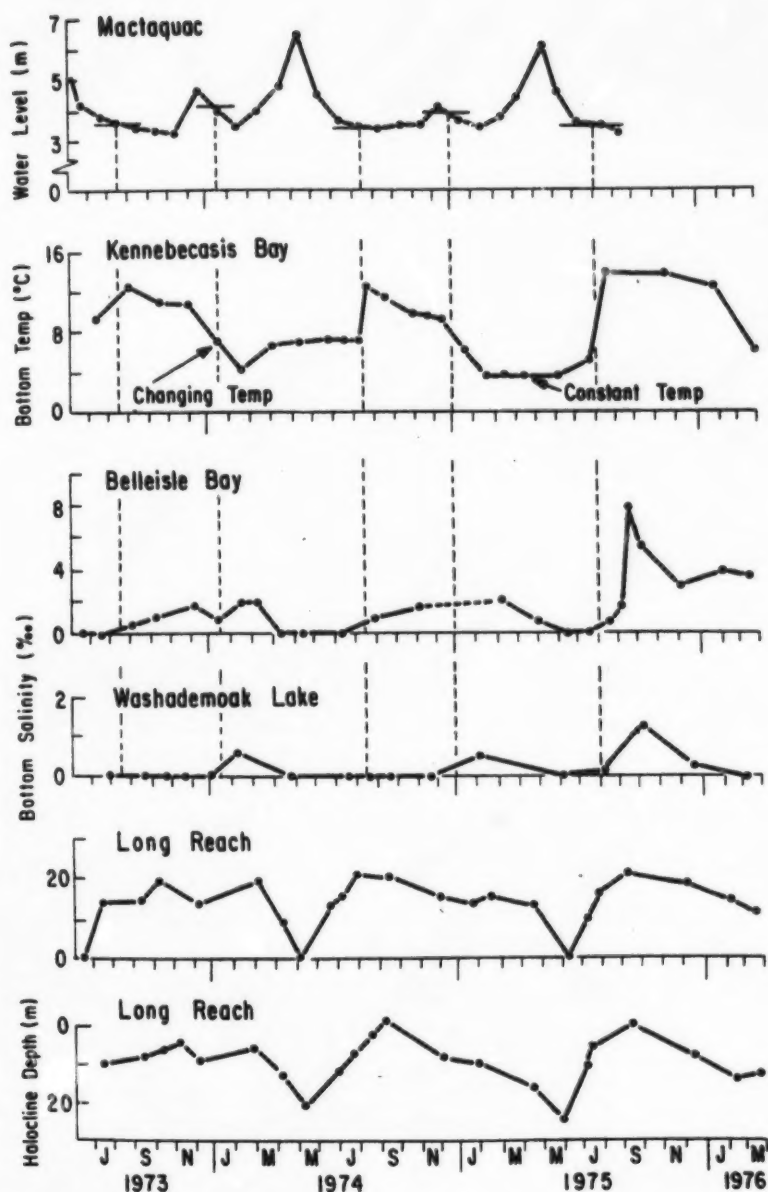


Fig. 10. Temperature fluctuations at three stations in the main stem of the estuary during 1974 and 1975.



11. Salinity isopleths at selected stations in the estuary during 1973-76. Station 6, Long Reach; Station K3, Kennebecasis Bay; Station B2, Belleisle Bay; Station W1, Washademoak Lake.



12. Fluctuations in temperature, salinity, and halocline depth at selected stations in the estuary in relation to fluctuations in water level at Mactaquac. Mactaquac, water level; Kennebecasis Bay, Station K3; Belleisle Bay, B2; Washademoak Lake, Station W1; Long Reach, Station 6; Long Reach, Station 6.

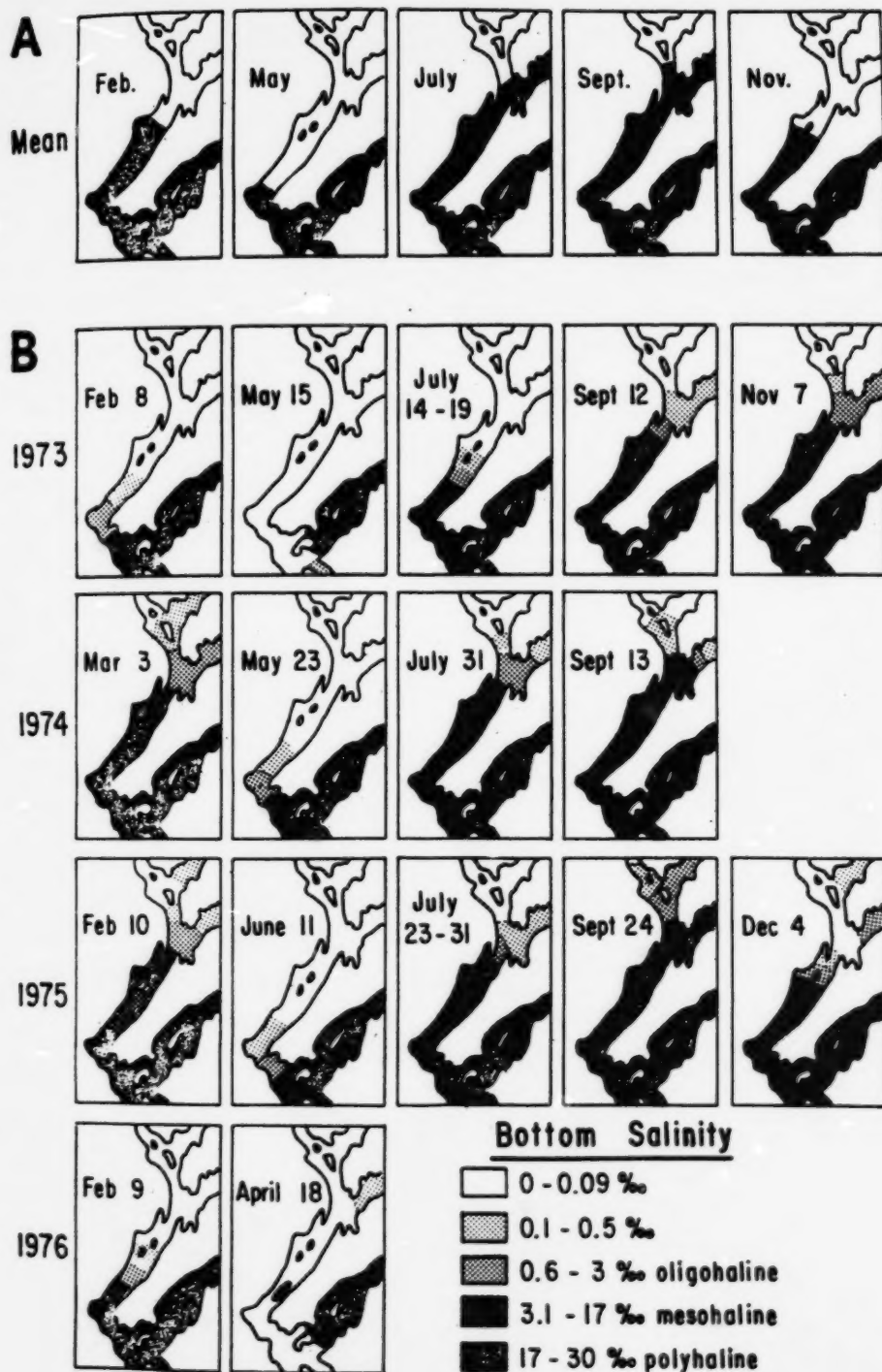
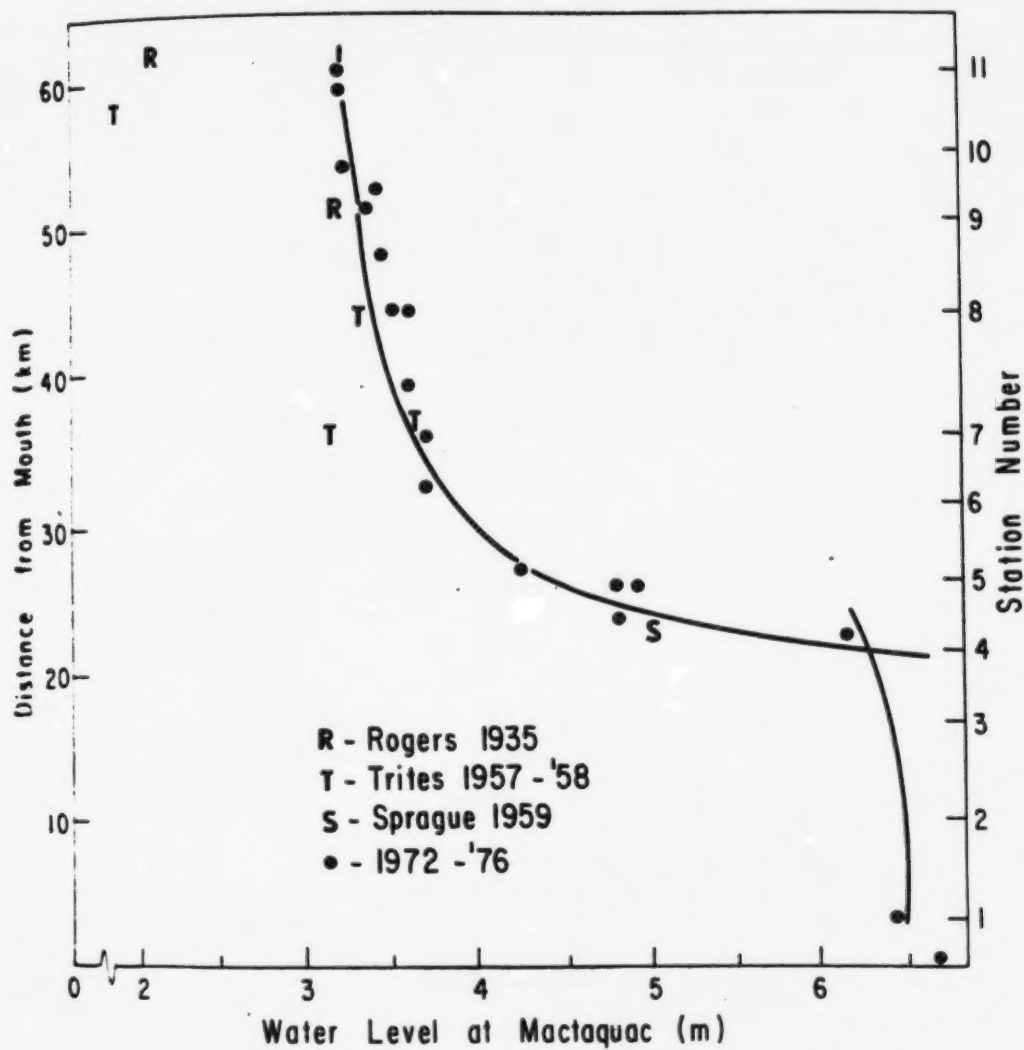


Fig. 13. A: Theoretical position of the estuary limit during mean monthly water levels in February, May, July, September, and November; B: Position of saline water on the bottom of the estuary at different times during 1972-76.



14. Relationship between water levels at Mactaquac and the upstream estuary limit (0.1⁰/oo) during 1972-76.

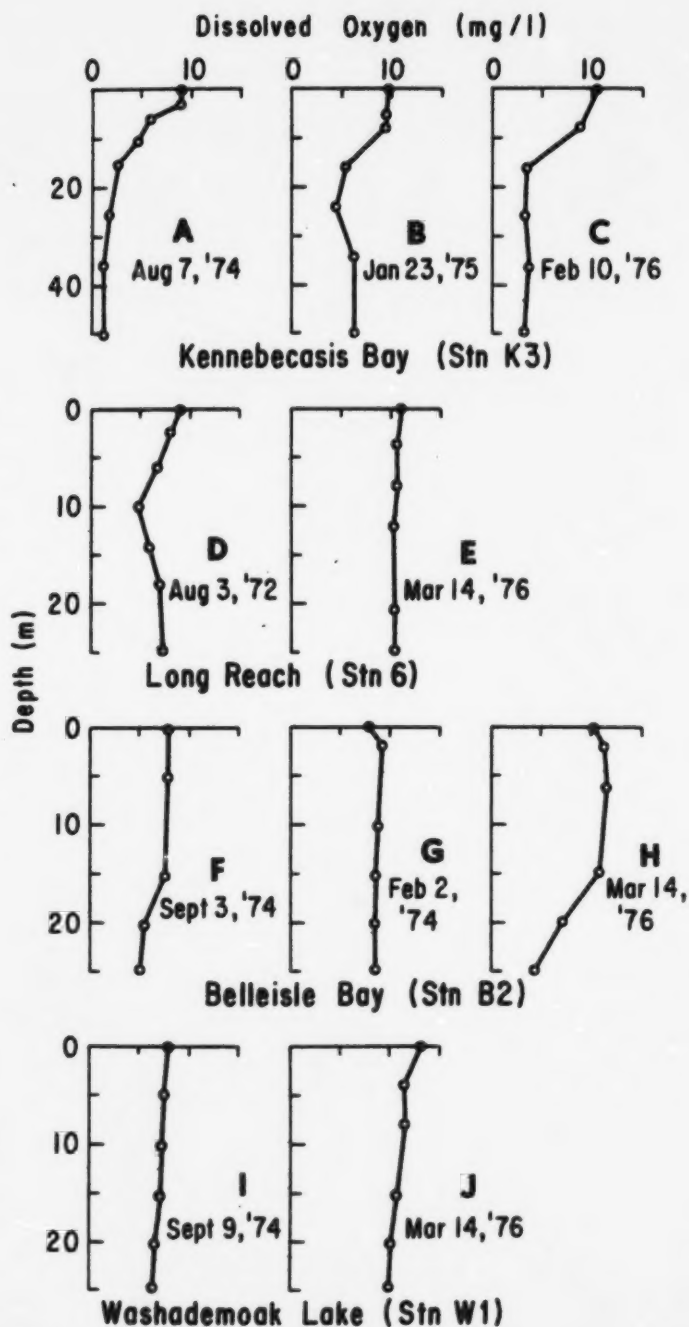


Fig. 15. Dissolved oxygen profiles at various stations in the estuary on selected dates during 1972-76.

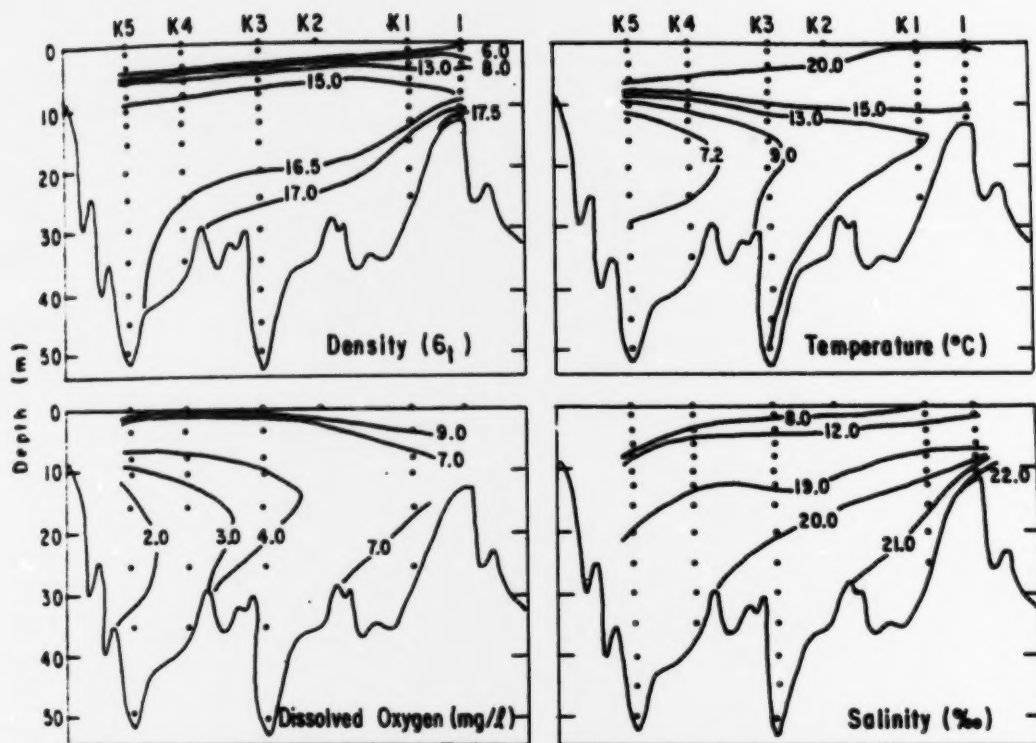


Fig. 17. Horizontal isopleths of density, temperature, dissolved oxygen, and salinity in Kennebecasis Bay on Aug. 21, 1974.

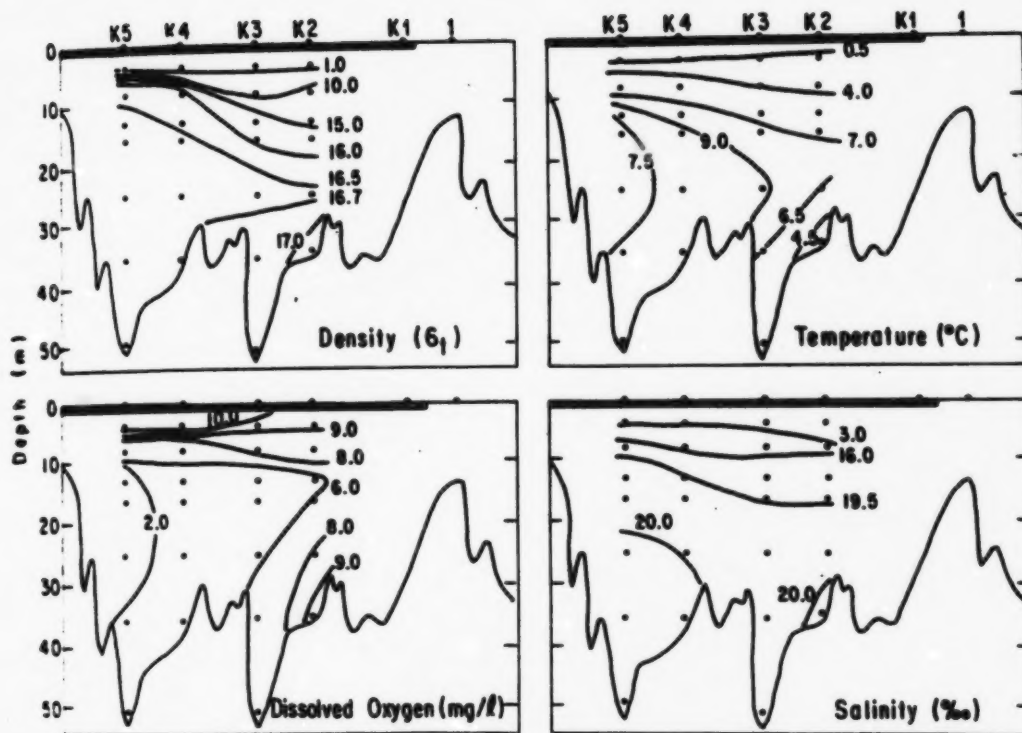


Fig. 18. Horizontal isopleths of density, temperature, dissolved oxygen, and salinity in Kennebecasis Bay on Jan. 23-28, 1975.

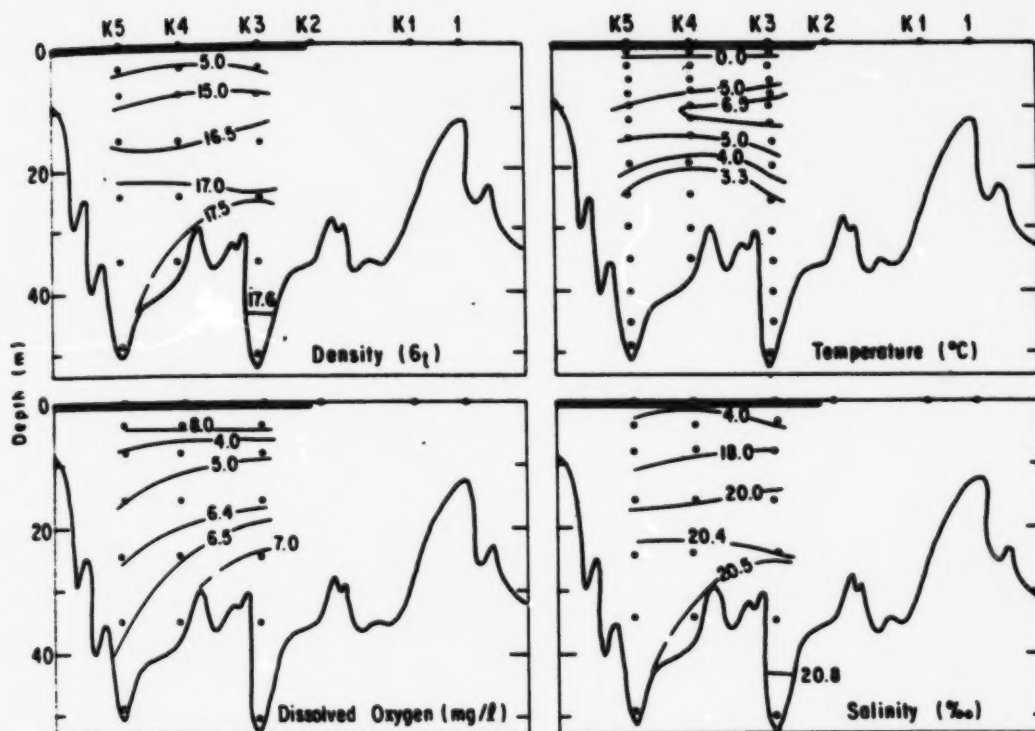


Fig. 19. Horizontal isopleths of density, temperature, dissolved oxygen, and salinity in Kennebecasis Bay on March 13, 1975.

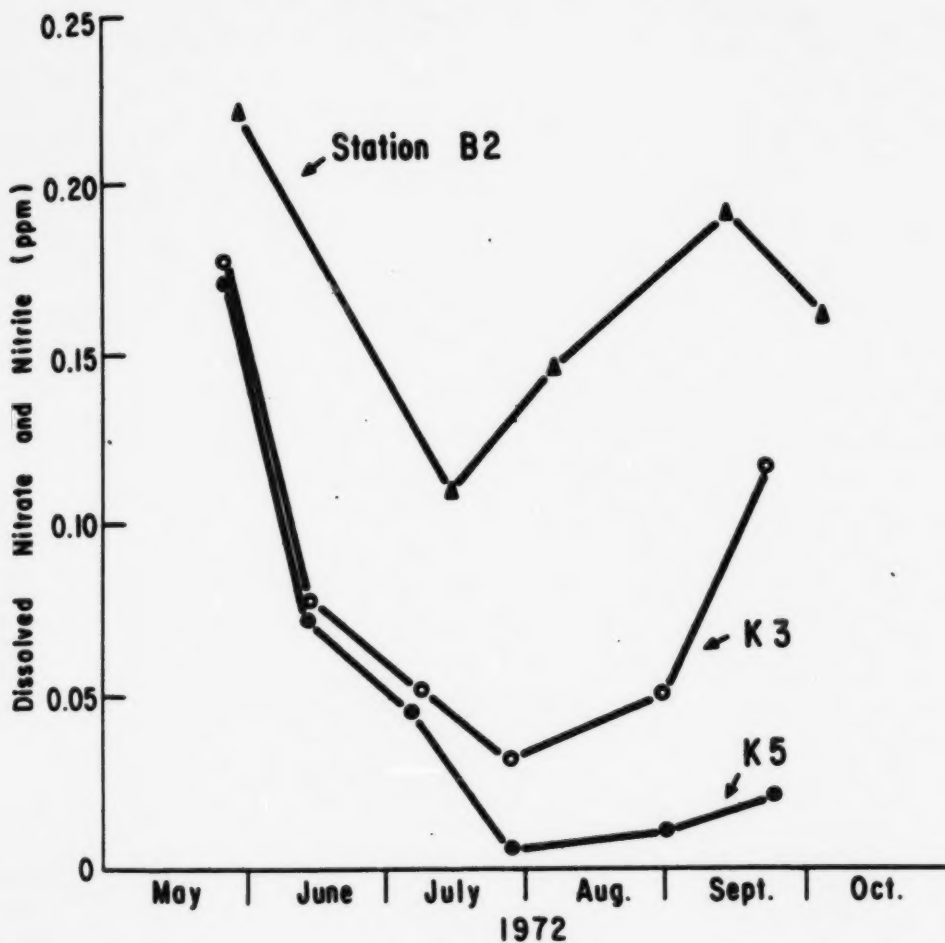


Fig. 20. Monthly dissolved nitrate and nitrite levels at three stations (K5, K3, and B2) in the estuary during the summer of 1972.

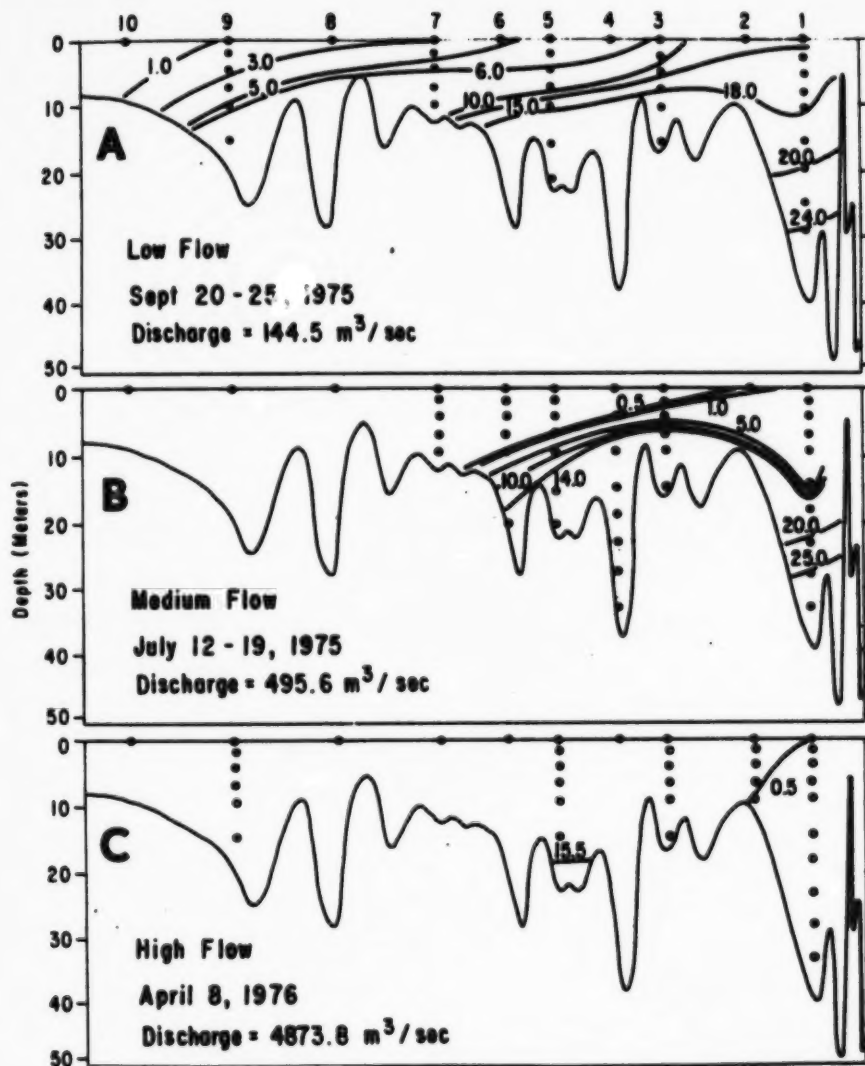


Fig. 21. Horizontal salinity isopleths in the main stem of the estuary during low, medium, and high river flow regimes.

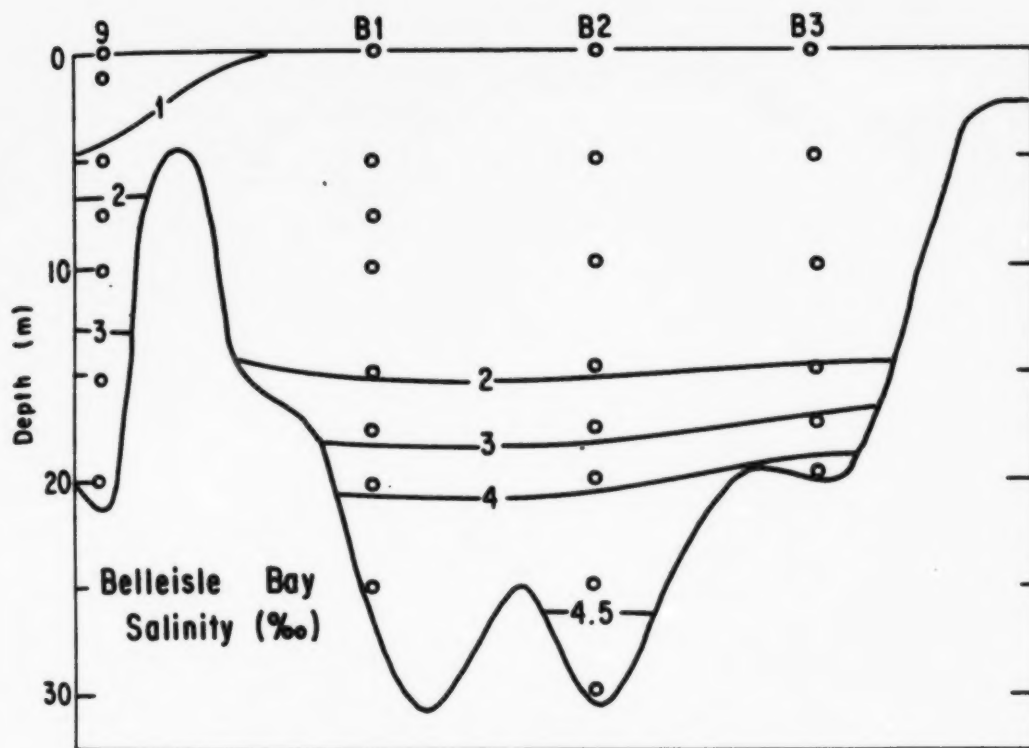


Fig. 22. Horizontal salinity isopleths in Belleisle Bay during November 1975.

POOR

QUALITY

ORIGINAL